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Indices for forecasting thunderstorms
Weather of 16–17 July 1797
Sensitivity of forecasts to humidity

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Thermodynamic indices for forecasting thunderstorms in southern Sweden

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Summary

Several verification scores have been used to investigate the performance of three thermodynamic indices as summer-time thunderstorm predictors. They are most efficient during the afternoon, when the 'best' index has a probability of detection near 100%. Combinations of two indices give better scores than single ones. Forward step-wise regression has been used to select the best predictors and estimate the lightning frequency. The analyses show a significant correlation between some indices and the frequency of lightning. Nomograms for estimating lightning probabilities and frequencies are suggested.

1. Introduction

The efficiency of some thermodynamic indices, used by the Swedish Meteorological and Hydrological Institute (SMHI) for forecasting purposes, has been investigated. The main use of these indices has been as 'yes/no' indicators. A thunder index is also needed in the new Swedish forecasting system (PROMIS).

Ideally, it should be possible not only to make yes/no forecasts, but also to give an indication of the lightning frequency. Even if simple indices such as these cannot be sufficient, some more information may perhaps be extracted from them. We have therefore also tried to use them, or combinations of them, to estimate the expected lightning frequency (expressed as the frequency of synoptic thunder observations). The main thunderstorm season in Sweden is summer, and only summer data were used. Hence, the results apply to summer. It may well be that these indices perform differently during other seasons, when thunder is much more rare. Also there are indications that the efficiency of the indices is dependent on the time of the day.

2. Lightning data and indices used

Since no lightning location system data were available to us, we used the observations made at ordinary 3-hourly synoptic stations to estimate the thunder frequency. Observations from about 20 synoptic stations, located as in Fig. 1, within the investigation area were used. The number of available observations was not constant since some stations make observations during only part of the day. Since we wanted an index expressing the thunder frequency during each 3-hour period, the code figures ww and W_1 in the present SYNOP code (World Meteorological Organization 1988) were used. The thunder index, *TH*, is defined as:

$TH = 100 \times$ (number of thunder observations)/(total number of observations).

A 'thunder observation' was defined as:

Thunder was observed during the last hour (ww = 29, 91, 92, 93 or 94 according to the present SYNOP code

of the World Meteorological Organization) or during the observation period (ww = 17, 95, 96, 97, 98 or 99).

Thunder was observed during the last 3 hours preceding the observation ($W_1 = 9$).

If both conditions are satisfied the observation gives a contribution of 2 to the numerator of *TH*. Hence, the maximum possible value of *TH* is 200. Some ambiguity arises here because W_1 describes the weather since the last main synoptic hour (0000, 0600, 1200 or 1800 GMT), not since the last 3-hour observation. Consequently some old thunder observations may linger, for instance thunder observed at 1330 GMT gives a contribution to *TH* for 1800 GMT.

We have tested three indices used by the SMHI:

$$K = T_{850} - T_{500} + T_{d850} - (T - T_d)_{700},$$

$$KO = (\theta_{e500} + \theta_{e700} - \theta_{e1000} - \theta_{e850})/2, \text{ and}$$

$$EI = -R_d \int_{p=p_m}^{p=400} (T_p - T_e) \times d(\ln p) \qquad \text{(Stone 1984)}$$

where p is in hectopascals (hPa) and

T = temperature (K) at the pressure levels (hPa) given by the index,
T_d = dew-point (K) at the pressure levels (hPa) given by the index,
θ_e = pseudo-adiabatic equivalent potential temperature (K) of the pressure levels (hPa) given by the index,
R_d = the gas constant for dry air,
T_e = environmental temperature (K),
T_p = temperature (K) of the rising parcel, allowing for an entrainment of 10% per 5000 m, and
p_m = the pressure level below 850 hPa where θ_e has its maximum.

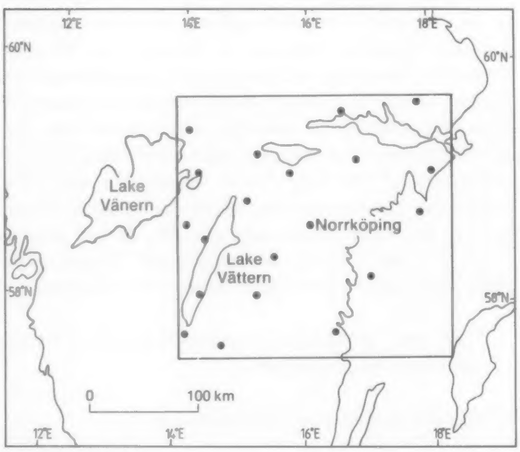

Figure 1. The investigation area and positions of the synoptic stations.

The index *EI*, also called the energy index, is thus an area on a thermodynamic diagram, expressing the change in energy for the moving parcel.

The *K* and *KO* indices were available both from analyses and from forecasts, while the energy indices, *EI*, were available only from analyses. The analysed indices were computed from the 0000 GMT data, and extracted from maps. Those indices were considered valid during the following 24 hours, i.e. from 0000 to 2400 GMT and will here be denoted by *KA* and *KOA* respectively.

Eighteen- and 30-hour forecasts of *K* and *KO*, valid at 0000 and 1200 GMT from the SMHI's limited-area model, will be denoted *KP* and *KOP* respectively. Those valid for 0000 GMT will be considered valid from 1800 GMT the preceding day to 0600 GMT, and those for 1200 GMT from 0600 to 1800 GMT. A diurnal variation of these indices will thus be at least crudely depicted by *KP* and *KOP*, but not by *KA*, *KOA* and *EI*.

3. Occurrence and non-occurrence

If $X11$ = number of cases when the event is forecast and observed,
$X12$ = number of cases when the event is not forecast but observed,
$X21$ = number of cases when the event is forecast but not observed, and
$X22$ = number of cases when the event is not forecast and not observed,

then the following are defined:

$pd = 100 \times X11/(X11+X12)$ = 'probability of detection',
$pf = 100 \times X21/(X11+X21)$ = 'probability of false alarm',
$ps = 100 \times X11/(X11+X12+X21)$ = 'threat score',
$V = (X11 \times X22 - X12 \times X21)/\{(X11+X12) \times (X21+X22) \times (X11+X21) \times (X12+X22)\}^{1/2}$, which is Yule's index (Meteorological Office 1975),
$yi = 100 \times V$, and
$pei = 100 \times \{X11/(X11+X12) + X22/(X21+X22)\} - 100$, which is Peirce's index.

For perfect forecasts $X12 = X21 = 0$, $pd = ps = 100$, $pf = 0$, $yi = pei = 100$, i.e. all occurrences of the event are detected and no false alarms are given.

For totally wrong forecasts $X11 = X22 = 0$, $pd = ps = 0$, $pf = 100$ and $pei = yi = -100$.

The indices *pd*, *pf* and *ps* only give measures of the efficiency of the method when the event occurs and/or is forecast, but do not involve correctly forecast non-occurrences. The indices *yi* and *pei* also take into account the latter, and hence are better measures if non-occurrences are important. If 'occurrence' is denoted by 1 and 'non-occurrence' by 0, Yule's index, *V*, is the correlation coefficient between forecast and observed events. For a thorough discussion of verification parameters the reader is referred to Daan (1984) or Ivarsson (1982).

Thresholds of *K* and *KO* used are those applied by the SMHI (Nilsson 1987):

$K \geqslant 20$,
$KO \leqslant 4$ (note that *KO* decreases with decreasing stability).

EI has not been used before by the SMHI so we had to choose a threshold. The *EI* are computed from the night soundings (0200 hours local summer time). It is remarkable that they were always negative. In reality the *EI* should have a daily variation with higher values in the afternoon, but the daytime–night-time difference should be fairly small. It would be interesting to see how forecast *EI* works, and we plan to include this index in future work. From our sample we chose −70 as the threshold.

As 'ground truth' we have used the thunder index, *TH*, described earlier. Inland summer thunderstorms have a pronounced daily variation. Since our analysed indices are considered valid for 24 hours, they certainly cannot represent this variation. Moreover, *K* depends only on conditions at and above 850 hPa and can hardly have any diurnal variation. Hence, its efficiency should have a diurnal variation. Inspection of our data confirms this and Fig. 2 moreover shows a diurnal variation of the efficiency of forecast indices when considering the conditions below 850 hPa. The efficiency has a pronounced night minimum. It is, however, noticeable that radar thunder indices, which actually measure some physical properties of the cumulonimbi, show a similar behaviour (Lopez *et al.* 1986, Andersson *et al.* 1989).

We have therefore confined our analyses to daytime, 0900–1800 GMT. For the first tests we have used the three 3-hour periods of each day, though these data are not independent. As Table I shows, *KOP* and *EI* perform best, though *KA* has the highest probability of detection. The latter feature was also noticed by Nilsson (1987). It is remarkable that the forecast *K* does not perform better than the analysed one.

When interpreting these figures we must remember the definition of *TH*. *TH* is the frequency of thunder observations. The highest *TH* recorded for this period is 53, i.e. at most about half the stations have recorded thunder during a 3-hour period. Even if thunder is known to be difficult to observe and several thunder occasions are not reported by the stations, we must conclude that even a 'correct' thunder forecast implies that several stations will not report thunder. This is even more true if a 'thunder day' is defined as a day when any station in an investigation area has reported thunder at any observation period.

Pickup (1982) noted that a kinematic parameter (curvature of the flow at 500 hPa) added valuable information to a thermodynamic index. Michalopoulou and Jacovides (1987) made the same conclusion for afternoon thunderstorms during spring over Cyprus. The curvature of the flow is not the only possible parameter; the relative vorticity or the horizontal divergence are others. In a qualitative sense the curvature of the flow is, however, easier to extract from forecast charts.

To test this effect on our data we made a subjective classification of the 500 hPa flow into anticyclonic, indeterminate or 'straight', and cyclonic, at 0000 and 1200 GMT. The 1200 GMT value was considered valid between 0600 and 1800 GMT and the 0000 GMT value between 1800 GMT the preceding day and 0600 GMT. The 0000 GMT data were extracted from the 36-hour forecasts from the European Centre for Medium-range Weather Forecasts and the 1200 GMT data from the 24-hour forecasts.

When testing the *KOP* index, using the combined criteria:

$KOP < 4$, and cyclonic curvature at 500 hPa,

we found a slight improvement in the sense that *yi* and the threat score, *ps*, increased somewhat, as shown in Table I. However, both the probability of detection, *pd*, and of false alarm, *pf*, decreased. The *pd* decrease is

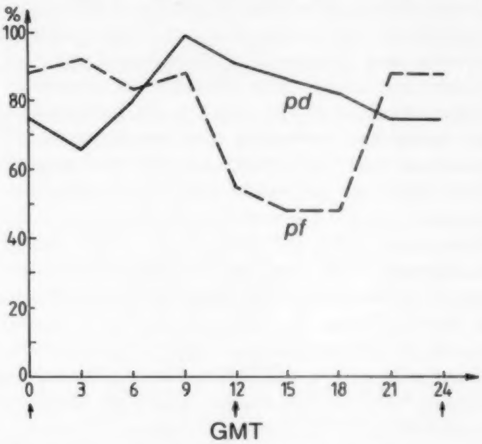

Figure 2. Diurnal variation of 'detection probability' (*pd*) and 'false alarm probability' (*pf*) using the thunderstorm indicator *KOP*. Arrows indicate validity times for *KOP*.

Table I. Verification scores for thermodynamic indices versus thunder ($TH > 0$) for the Norrköping area, from 27 May to 17 August 1987, 0900–1800 GMT

Index	Threshold	*pd*	*pf*	*ps*	*yi*	*pei*
KA	20	93	63	35	44	56
KP	20	71	67	28	29	36
KOA	4	58	59	31	34	38
KOP	4	86	50	45	55	66
EI	−70	84	51	44	52	64
KOP/curvature	4/cyclonic	80	41	51	60	68
KOP/*EI**	5/−85	100	37	62	70	80
KOP/*KA**	5/15	100	40	55	64	74

* One 9-hour period. Entries without * contain three periods of 3 hours.

unfavourable. The increase of *yi* is not as large as that found by Michalopoulou, though our *yi* for the period 0900 to 1800 GMT reaches 60.

Hitherto we have used 3-hour periods. Often forecasts are made for a longer time-period. We have therefore combined the three 3-hour periods between 0900 and 1800 GMT into one. A thunder observation in this data set then only requires thunder to have been observed in one of the 3-hour periods. Repeating the tests on this data set showed, however, only small improvements.

In this study all kinds of thunderstorms are included. Some indices may be better in forecasting air-mass thunderstorms, while others may treat the environment for squall lines and frontal thunderstorms better. Unfortunately our data set is too small to make such subdivisions, which moreover would introduce a new element of ambiguity. However, we have combined the 'best' thermodynamic indices. When using such combined indices one may choose less restrictive thresholds for each index. The best result ($ps = 62$, $yi = 70$, $pei = 80$) gave a combination of *KOP* and *EI*, as in Table I.

Stone (1985) has computed point biserial correlation coefficients between various thermodynamic indices and the occurrence or non-occurrence of radar echoes above different reflectivity thresholds, as well as similar correlations for 'severe weather'. Stone used only daytime data. Amongst his indices were *K* and *EI*. The highest correlations were found for the occurrence of reflectivity above 41 dBz, which 'is generally considered the lowest level associated with thunderstorms'. The maximum correlation (0.65 and 0.59 for the periods 1800–2400 and 0000–0600 GMT, respectively) was reached with *EI*. The corresponding figures for the *K* index were 0.53 and 0.53. For 'severe weather', considerably lower correlation coefficients were found, about 0.2, but also here the *EI* performed better than the *K*. We also found *EI* a better thunderstorm predictor than *K*. Roughly, Stone's correlations can be compared to our *yi*. Our figures, as well as those we have quoted, indicate then that only modest success can be expected from this type of index. Improvement needs the introduction of some new input data, which could be some parameters from numerical forecasts, as indicated earlier. Such parameters could be the relative vorticity, a measure of the baroclinicity, a measure of the accumulated convective precipitation, etc. It is of course also possible to design a new thermodynamic index, but there is already an overwhelming number of these, containing more or less probable combinations of temperature and humidity at different pressure levels, and none has proved to have an outstanding efficiency. The *KO* and *EI* indices at least have a sound background in the ideas of potential instability and parcel convection.

4. Skill score and a nomogram for lightning probability

For these analyses we have used the period 0900–1800 GMT, combined into one data set.

The skill score, *S*, is defined as (Daan 1984, Ivarsson 1982):

$$S = 100 \times (1 - B/Bk)$$

where B = Brier score for the forecast, and
Bk = Brier score for a control forecast.

The Brier score is defined as:

$$B = \Sigma(f-d)^2/N$$

where $d = 1$ if thunder is observed ($TH > 0$),
$d = 0$ if thunder is not observed ($TH = 0$),
f = forecast probability of thunder, and
N = number of observations.

We then have to assign a sample climatological probability for thunder, i.e. a probability that at least one station in the area shall report thunder on at least one of the three observations within the period 0900–1800 GMT. The probability that a single station reports thunder during the day is about 0.13, but the probability that any station does so is higher, because a thunder area may cover only part of the investigation area, and few flashes may pass unnoticed.

We have chosen the sample climatological probability as 0.25. Climatological forecasts, i.e. forecasts always giving the probability 0.25, give $Bk = 0.25 - 0.25^2 = 0.19$ and $S = 0$, while perfect forecasts give $B = 0$ and $S = 100$.

We also have to assign probabilities to each value of our predictand or, if we have chosen a combined index, to each pair of predictands. Probabilities used are shown in Fig. 3. The reason for choosing *KA* and *KOP*

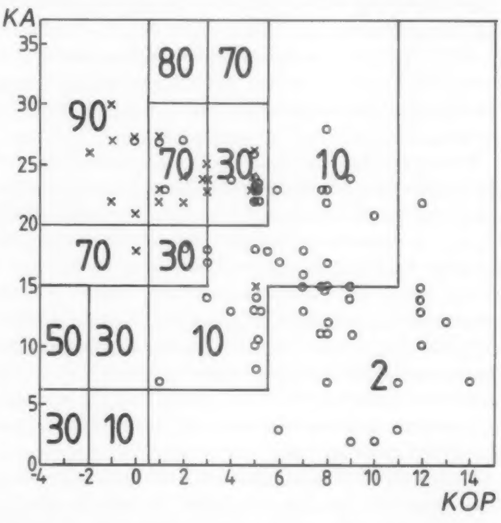

Figure 3. Nomogram for expected daytime lightning probability. Crosses indicate thunder ($TH > 0$), open circles indicate no thunder ($TH = 0$).

instead of *KOP* and *EI*, which gave somewhat better scores according to Table I, is that *KA* and *KOP* are selected by the regression analysis in section 5.

For the combined index *KOP*/*KA* in Table I we have used a threshold of 15 for *KA*. In Fig. 3 we have supposed thunder also for lower *KA*, provided *KOP* is low, that is the air mass is convectively (potentially) unstable. If lifted, the initially stable air mass (small *K*) will increase its lapse rate. During the summer of 1986 we noted some cases of thunderstorms with low *K* and *KO* values (Nilsson 1987). From a forecasting point of view it is also reasonable to lay some more weight on *KOP*, since it is a forecast value and may depict a weather change.

Table II gives skill and Brier scores for the indices used and some combinations of them (the assigned probabilities are only shown for the combination of *KA* and *KOP* in Fig. 3). It is apparent that combinations of two indices give better scores than a single one. We also believe that the nomogram in Fig. 3 is a more efficient forecasting tool than the 'yes or no' answers from single indices or combinations of them.

Table II. Skill and Brier scores for thermodynamic indices versus thunder ($TH>0$) for the Norrköping area, from 27 May to 17 August 1987, 0900–1800 GMT

Index	Skill score	Brier score
KA	22	0.15
KP	2	0.19
KOA	32	0.13
KOP	38	0.12
EI	41	0.11
KOP/*EI*	54	0.08
KOP/*KA*	52	0.09

The sample climatological probability is 0.25.

5. A nomogram for lightning frequency

The analyses of 'occurrences and non-occurrences' are useful for probability forecasts. However, the frequency of lightning is also important. An index should be able to give an acceptable estimate of the thunder activity as expressed by *TH*, which can be regarded as a crude measure of the lightning frequency within our area. We have used forward step-wise regression to select the best predictors and estimate *TH*.

The frequency distributions of our indices are quite different from that of *TH*, which is positively skew. To transform our indices to positively skew distributions we made the transformation:

$$e^{(\text{index}-rr)/tt}$$

where *rr* and *tt* are values to be chosen and e is the base of natural logarithms. The transformed distribution should be such that to the left of the value *rr* the transformed index is constant or grows very slowly, but to the right it grows quickly without attaining unreasonably high values for possible values of the index. The following transformations were chosen:

for *K*: $e^{(K-15)/5}$,
for *KO*: $e^{(6-KO)/2}$, and
for *EI*: $e^{(EI+100)/25}$.

Making the regression on the daytime (0900–1800 GMT) data with the confidence levels 0.01, 0.01 (for acceptance and rejection) gave:

$$TH = -0.47 + 0.48 \times e^{(KA-15)/5} + 0.48 \times e^{(6-KOP)/2} \quad (1)$$

with an explained variance of 37%.

This analysis indicates that *KA* and *KOP* are the 'best' predictors. The explained variance, corresponding to a coefficient of correlation of about 0.6, is low. However, bearing in mind the absence of good methods for thunder forecasting, the relation should have some prognostic value, especially since it gives not only a 'yes or no', but also an indication of the lightning frequency. For such purposes a classification scheme is needed, which takes account of the fact that the constant term in the equation is a 'statistic' effect, which of course does not mean that a negative number of lightnings should be expected or that lightning should always be expected. Such a classification is suggested in Fig. 4.

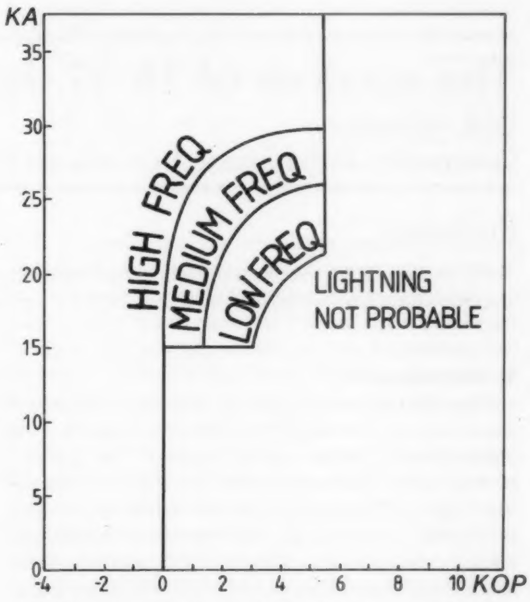

Figure 4. Nomogram for expected daytime frequency of lightning.

6. Conclusions

Three thermodynamic indices for thunderstorms have been tested. Their efficiency has a diurnal variation with maximum during the afternoon. The best scores

were obtained for daytime thunderstorms with a combination of two indices. A combination of *KOP* and *EI*, as well as of *KA* and *KOP*, detected all daytime thunderstorms with a probability of false alarm of about 40%. This level of performance will probably not be achieved in a new independent sample, but nevertheless improvements seem possible. The use of a forecast *EI* valid at the actual time as well as the introduction of a kinematic parameter from numerical forecasts are possible ways to achieve this.

A nomogram of expected daytime lightning probabilities is presented as a possible forecasting tool. There is a significant correlation between the *K* and *KO* indices and our measure of the lightning frequency, though the correlation is fairly low. With the inherent difficulties in forecasting thunderstorms it nevertheless may have a prognostic value, and a nomogram for the expected daytime lightning frequency is presented as a possible forecasting tool.

Acknowledgements

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The weather of 16–17 July 1797

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Summary

Historical data sources from the late eighteenth century are used to reconstruct the synoptic conditions during a thundery outbreak that affected much of England on 16 and 17 July 1797.

1. Introduction

This paper uses contemporary sources to reconstruct conditions of mid-July 1797 when severe thunder was observed over a wide area of England. The apparent severity of the weather served to provide an unusually rich legacy of accounts, not only from the weather enthusiasts of the time, but also from a welcome diversity of other sources. However, it must be stressed that the study is offered for its intrinsic interest and as an example of how far sources from such distant times can be used by those with an interest in 'historical meteorology'; by itself it does not indicate any essential difference between the climate of the 1790s and that which prevails today.

Even in the normal course of events, weather information from the late eighteenth century is not scarce, but caution must be exercised in the use of its seeming abundance. Instrumental data may have the appearance of accuracy but, being taken in an age before either observational procedures or the instruments themselves were standardized, interpretation must be undertaken with great care. Even qualitative descriptions do not free the reader from the hazard of misinterpretation. Terms such as 'hurricane', 'tornado' and 'great storm' (the latter too often cited as 'the worst in living memory' for comfort) are employed with inconsistent abandon, while descriptions such as 'fair', 'fine' and 'cloudy' are used so frequently that they cannot but embrace a wide range of conditions. Nevertheless, the pioneering work of Manley (1974), Lamb and Johnson (1966) and, more recently, Kington (1988) have amply demonstrated the

rich harvest that may be garnered by the judicious sifting of old material.

2. The weather of July 1797

Manley's Central England Temperature (CET) record reveals the month to have been unusually warm. The CET figure of 17.3 °C is well above the 30-year mean of 16.1 °C. Lewis (1947) has also suggested the summer to have been London's warmest since 1780. Lamb (1982) has observed '...the 1790's and the first years of the new century produced a number of pleasant summers in England...'.

Turning to the specific events of 16 July 1797, the clearest and most evocative picture is created by the contemporary descriptions. The following citations are drawn from meteorological diaries as well as more general accounts by non-meteorologists who were clearly much impressed by the events they witnessed. It would be helpful for the reconstructions to have a better time-scale by which to gauge the progress of the storm; sadly such detail is lacking and diary entries tend to be by days with little reference to precise hourly timing.

The story begins on the night of 15/16 July with a record in the log of HMS *Director*, moored in Yarmouth Roads (Norfolk), of thunder to the east but with no further record until the evening of the 16th at which point several land stations pick up the story. At Shukborough (near Daventry) [now spelt as Shuckburgh] the weather diary reads '...thunder and rain in west...'. While at Modbury (Devon) one finds '...much distant thunder and some rain...'. Neither diary gives any indication of the time of onset of thunder. In the north of the country the Newcastle-upon-Tyne publication *Local Records* (Sykes 1833) contains the following entry:

> July 16th. There was a most terrible tempest of thunder and rain in the neighbourhood of Newcastle. To the eastward of that place it was truly awful. At Whitley Camp the lightning set fire to the whins placed as a facing to the sheds of the East and West Lothian Cavalry and the wind blowing briskly, the whole line was almost instantly ablaze.

A subsequent note in the *Gentleman's Magazine* for September 1797 gives the time of this event as between 5 and 6 o'clock but it is uncertain whether the writer refers to that time on the evening of the 16th or the early hours of the following day. The former interpretation places it five hours earlier than any other land station for which we have evidence of timing. On the other hand the latter interpretation would be accommodated more easily within the general thunder period which from all other records is placed between dusk (about 2200 hours) on the 16th and dawn on the 17th. Baker's *Record of the Seasons* makes reference to the night of the 16th as '...extremely dark and tempestuous...'; unfortunately no indication of place is given. However, for the most complete and vivid description of the storm the same edition of the *Gentleman's Magazine* as cited above has no rival and it repays lengthy recounting:

> PARTICULARS OF THE LATE STORMS. At Lewes, on Sunday 16th July, with little wind and a cloudless sky, the thermometer before 2 o'clock was 80 deg. of Fahrenheit's scale; the barometer at 30 deg. 20 min at which degree it had been stationary 24 hours... the sun set with great splendour, though some broken clouds were seen in the western horizon. Soon after sun-set the inhabitants of the Western parts of this country (*sic*) observed extensive cloud approaching from the South West, with little wind, but the flashes of lightning were very frequent, and the peals of thunder extremely loud with rain falling in heavy showers. The first storm had spent its force about twelve o'clock; and before one an extensive cloud, with brisk gale, had again overspread the horizon; the flashes of lightning succeeded each other so incessantly, that the interval seldom exceeded 12 or 13 seconds of time... the obscurity of the intervening spaces, and the rain pouring down in such a continual stream, could only be exceeded by a tropical tornado. On Monday by noon, the levels were completely inundated, as they generally are after 24 or 36 hours rain in the winter season. The storm was felt with equal severity in this town and the neighbourhood, where it commenced with twilight, and did not fully subside until four the next morning.

The anonymous reporter goes on to cite storm damage at places as widely separated as Yateley (Hampshire), Stamford Bridge (Humberside) and Oxford. A later edition of *Gentleman's Magazine* contains a report of thunder over London. The newspaper entry is again eloquent testimony to its intense activity:

> July 16th. We experienced in London a thunderstorm, accompanied by immense torrents of rain, more awful and tremendous than anything of the kind ever before remembered by the oldest inhabitant of the metropolis. From about 12 at night till 4 in the morning the Eastern sky presented the most terrific appearance, the fiery agitation of the firmament seeming momentarily to threaten the earth with universal conflagration. Of the dreadful flashes and the awful peals of thunder that prevailed, no adequate description can possibly be given; the mere recollection of them is painful, and the consequences cannot be contemplated without emotions of horror — The storm passed over the Continent previous to visiting this country. It was felt at Lille on Saturday afternoon, and continued till three o'clock without intermission.

The subsequent list of places similarly affected included Croydon, Petersfield, Gosport, Isle of Wight and Church Watton (Wiltshire) while at Prior's Lee (Shropshire) it was observed that '...a great ball of fire fell upon a large stack of two-year old hay, and passed through it making a large perforation into the ground.' It is a matter of regret that no indications of times are given in the records of those locations.

The record of an approach of a storm from the east, implicit in the second *Gentleman's Magazine* account contrasts with the western approach cited in the first of the apparently two storms to strike Lewes. The log of HMS *Director*, then moored at Yarmouth, records thunder and lightning to the east during the early hours of the 16th, but to the north-west later in the day when the weather is described as 'hot and sultry'. The storm(s) appear to have subsided over England on the 17th. The entry in William Bent's (London) diary for the 17th describes the events of the previous night; '...much vivid lightning in the west last night and early this morning a most tremendous storm...', but nothing thereafter.

Baker's note for the 18th (*sic*) refers again to the events on the night of the 16th and is a somewhat garbled version of the *Gentleman's Magazine* report. Only in Edinburgh is there reference to thunder on the 17th exclusively. George Waterston's diary entry for that day reads '...thunder and lightning — day very warm. Thermometer 70.' The prefix 'M' to this note indicates 'morning' but the precise hour is unknown. There is no corresponding entry for the previous evening.

It is against this tempestuous background that the instrumental record covering the storm period and the days immediately beforehand can be examined. As many instrumental data as could be gathered have been used. In most cases standardization or correction of the data is impossible without increasing the further likelihood of error. Data are presented as they were recorded. Exposure, recording times and the quality of instruments are all variable but to an unknown degree, these inconsistencies being reflected, for example, in the contrast between the temperatures recorded at two of the London sites (Table I). Both records, however, appear to be well kept and dutifully observed. The absolute figures must be treated with caution, and in isolation can convey little information. But when set against the record for the year as a whole one significant fact emerges; the period 14 to 18 July was, in all cases save one, the warmest of the year. The single exception was Modbury where late July was marginally warmer. Table I summarizes the recorded temperatures for the period.

Table I. Daytime maximum temperatures (°F) for various sites for mid-July 1797

Location	14th	15th	16th	17th
London (Royal Society)	84.0	81.0	84.0	83.0
London (William Bent)	73	72.5	74	74
London (Clare Street)	76	74	72	75
Derby	78	78	75	76
Modbury	59.0	59.3	60.0	61.0
Shukborough	76	79	80	80
Stroud	67	63	65	67
Edinburgh (as reported in the *Edinburgh Magazine*)	74	66	70	68

Readings were all taken between the hours of 12 noon and 2 p.m. local time and may be considered as the maxima. Fractional parts are given when recorded as such, elsewhere the absence of a fraction denotes that whole numbers only were entered in the source document.

The rainfall record shows a dry month for England, although Edinburgh was much wetter than normal. Adie's record (see Forbes 1861) for the city gives a total of 5.19 inches against a 1795–1850 mean of 2.89 inches. Most English stations were drier than average; William Bent (London) recorded only 1.42 inches. There was little rain in the days before the thunder, most stations recording 'nil'. The Royal Society record, however, notes 0.42 inches for the 16th out of a monthly total of 1.29 inches.

Of equal importance in any attempt to reconstruct past synoptic conditions is wind direction. Here, more than with temperature and rainfall, individual site inaccuracies are easily detected in wind directions that are inconsistent with those from surrounding stations. Wind data are summarized in Table II. The only anomaly is the easterly wind recorded for the London sites. In view of the general care exercised in the preparation of both data sets and the consistent records shown at other times, the easterly winds are best interpreted not as errors but as evidence of sea-breezes working along the lower Thames valley and created in an otherwise settled and very warm spell. Their disappearance with the onset of less settled weather later in the month supports such a hypothesis. The dominant winds were from between south and south-west. Wind speeds are less easy to determine. Royal Navy logs appear to have used a system all but identical to that later codified by Admiral Beaufort and give the best indications of speed in terms likely to have a similar meaning today; the values from HMS *Director* are used to supplement Table II. Many land-based stations preferred a much coarser scale of resolution ranging

Table II. Wind directions for various sites for mid-July 1797

Location	14th	15th	16th	17th
London (Royal Society)	E	E	SW	S
London (William Bent)	S(2)	SSW(1)	E(1)	SW(2)
London (Clare Street)	E	SE	SW	S
Derby	SE	SW	S	SW
Modbury	S	S	calm	SW
Shukborough	S	SSW	SSW	SW
Stroud	SbW(0)	SbW(1)	SbW(0)	W(1)
Yarmouth (HMS *Director*)	var(4)	SbW(4)	var(1)	var(1)

Figures in parentheses are wind forces given on an increasing scale of 0 (calm) to 4 (storm) for land stations and on the Beaufort scale for HMS *Director*.

from 0 (calm) to 4 (storm). Where available these 'forces' are listed in the table. The general impression gained, however, is one of light winds. Estimates must be approximate but an average of Beaufort force 3 gusting to force 5 is possibly representative.

Finally, the barometer records for the month are shown in Fig. 1. The data have not been reduced to sea-level equivalents because of the lack of information on the types of instrument used and their altitude above sea level (the record of the Royal Society barometer has been corrected by Eaton 1880). Although differences are apparent the records' series are remarkably, and encouragingly, consistent. Spells of high and low pressure can be easily distinguished and, with the exception of low pressure around the 6th and 30th, the conditions seem to have been dominated by high pressure. The mid-month period shows little tendency for any abrupt pressure changes although pressure on the 16th was consistently, but modestly, higher than on the 17th when a drop of some 3 mb occurred at all sites. It might be added that no evidence of steep pressure gradients across the country could be found on any day between the 12th and 25th; a conclusion confirmed by the light winds over the same period.

3. General conclusions and interpretation

In the most general terms, the accounts present a picture of severe thundery weather setting in on the night of 16 July and persisting till dawn over England, but possibly longer in Edinburgh. Even allowing for journalistic licence, the conditions must have been extreme. There is inevitable uncertainty concerning the number of storm cells and their movements. The Lewes report, detailed as it is, clearly indicates development from the west, but possibly only for the first of two periods of thunder. The Shukborough record also notes an approach from the west. Having observed thunder to the east only 24 hours earlier, the midnight watch (16/17 July) on board HMS *Director* note thunder to the north-west. At the same time William Bent's printed record also refers to thunder from the west. On the other hand the *Gentleman's Magazine* refers to the eastern sky as having '...presented the most terrific appearance, the fiery agitation of the firmament seeming momentarily to threaten the Earth with universal conflagration.' But might this refer not to an approach, but the retreat of the storm since no specific mention of 'approach' prefaces the latter observation? The same report also suggests this to have been the same thunderstorm that struck Lille in northern France (and lying due south-east of London) 24 hours earlier. This continental outbreak seems unlikely to be so closely linked with the London events particularly in view of the absence of any record of daytime thunder before the clearly documented onset of activity at dusk on the 16th. William Bligh's log kept on board HMS *Director* records thunder to the east as early as the night of the 15th/16th and this may well be part of the Lille thunderstorm, but there is no other mention in the record of thunder between that time and midnight of the 16th/17th. Whatever the precise timing, thunder was recorded extensively across England on the 16th from the Isle of Wight to Newcastle-upon-Tyne, and from Yarmouth to Devon.

The 16th had been, almost everywhere, the hottest day of the year with winds a light south to south-westerly, with perhaps some east coast sea-breeze

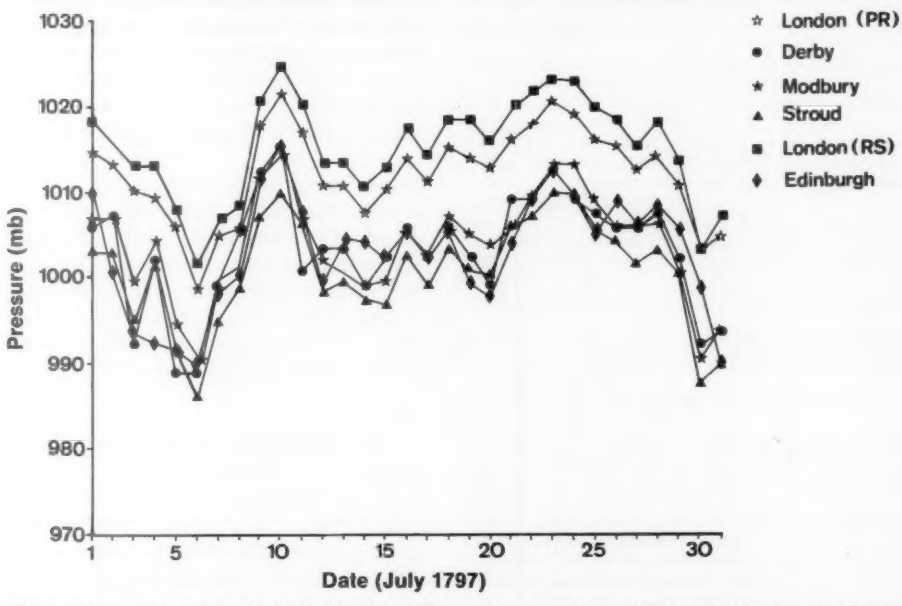

Figure 1. Barograph traces for various sites (see key) for July 1797 drawn from several sources. The two London sites are at Paternoster Row (PR) and the Royal Society offices (RS).

activity. There is no evidence in the barometer records of low pressure in the immediate vicinity and pressure was high everywhere and had been so for several days (cf. *Gentleman's Magazine* report and Fig. 1). In England the month had been generally dry, but much heavy rain clearly accompanied the thunder of the 16th.

The necessarily hesitant picture to be drawn from this information is of severe thunder approaching from some south-westerly point. With possible evidence from Newcastle, and the firmer evidence from Edinburgh, it appears that the disturbances moved northwards.

The degree of instability required to produce such thunderstorms indicates that, however poorly developed the pressure fields may have been at sea level, the middle- and upper-tropospheric circulation may well have been dominated by a cold pool or trough which, combined with known high temperatures at ground level, would create the necessary steep environmental lapse rates.

Some recently published case-studies are instructively comparable with this broad interpretation. Most importantly, Morris (1986) offers an example of the phenomenon known as 'the Spanish plume'; a situation in which warm Iberian air is drawn northwards beneath an advancing upper trough, leading to severe thundery outbreaks in France and the British Isles. Morris's example was of 19/20 May 1986. The sea-level and 1000–500 mb thickness charts for 0000 GMT on 20 May 1986 are shown in Fig. 2 and might indeed be similar to the prevailing situation on 16 July 1797. The southerly air flow, indeterminate sea-level pressure gradients and general state of the weather for 20 May 1986 are in broad agreement with those already described for 16 July 1797. The main period of thunder on the night of the 16th/17th was so extensive that, together with the possibility of progressive north or north-eastward movement following an advance from the west, it suggests the activity of an organized frontal feature ahead of a weakly developed surface low swinging across the country in the manner suggested in Fig. 3. The absence of strong winds and the persistently high pressure rule out any possibility of a deep low. The degree of instability necessary to induce thunder of such intensity is accounted for by the presence of a trough or cold pool above the low. The isolated thunder noted by

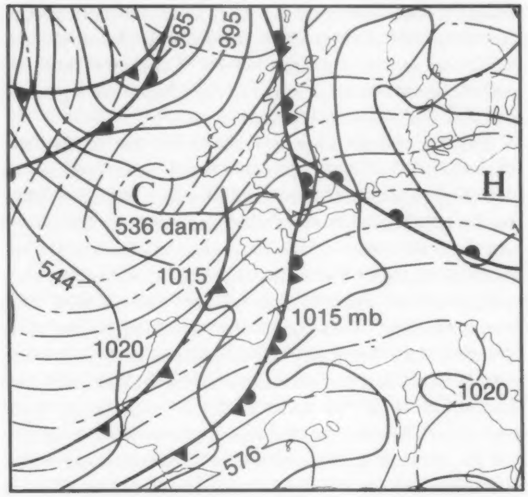

Figure 2. Surface pressure and 1000–500 mb thickness chart for 0000 GMT on 20 May 1986. (Redrawn from the charts of the *European Meteorological Bulletin*.)

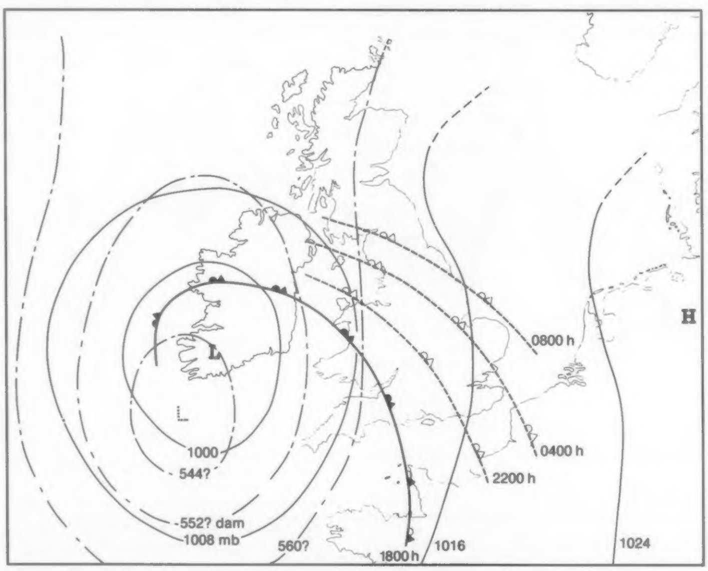

Figure 3. Generalized reconstruction of positions of pressure systems from 1800 hours on 16 July 1797 to 0800 hours on the 17th. Sea-level isobars and 500 mb height contours are shown, the question marks on the latter stressing their speculative values.

William Bligh on board HMS *Director* and the Lille thunder noted in the pages of *Gentleman's Magazine* are attributed to the general instability in the southerly air stream ahead of the front and not directly connected with it.

The importance of the ambiguity in the Newcastle record is now critical. If the events described took place at 5 or 6 o'clock on the morning of the 17th then, together with Waterston's Edinburgh record of thunder later that morning, a picture of steady north-eastward progress is complete. But if the events relate to 5 or 6 o'clock the previous evening there is less evidence of 'organization'. Reference to the stabling of the cavalry horses that broke away in fear hints at a night-time and not a late afternoon event but is scarcely conclusive. If the Newcastle thunderstorm did take place on the evening of the 16th then the picture created is one of much less regular and organized activity, suggesting random outbreaks within a generally unstable southerly air stream; a situation for which recent analogues have also been reported. In a study of an unusually severe hailstorm on 7 June 1983, Dent and Monk (1984) draw attention to the importance of '...warm advection of moist air ahead of an advancing upper trough.' The prevailing situation, though not reproduced here, was not unlike that described by Morris (1986). A shallow pressure gradient existed across western Europe between an anticyclone to the east and a shallow low north-west of Cape Finisterre (Spain). The consequent southerly air flow was overlain by an advancing trough. Hill (1984) and Wells (1983) also examined severe hailstorms from two days earlier along the southern coast, but within the same general synoptic conditions. The contrast with the events described by Morris is the absence of extensive thunder or hail organized along a well defined front. The outbreaks also occurred over a much longer time period than that in question. Such conditions might equate with a persistent run of sporadic outbreaks of the type hinted at by Bligh's record of thunder and the reference to thunder over Lille.

In conclusion, Fig. 3 is offered as the more probable of the two types described above. It is all but impossible to be confident but the marginal balance of evidence, the short time span of the various outbreaks over Britain, the likelihood (though not proven) of regular north or north-eastward movement, leans towards an organized frontal pattern of thunder, heralded by activity in the unstable southerly air stream to the east in the preceding 24 hours.

4. Supplementary note on data sources

Material used in this paper was drawn from a number of sources. The printed weather diaries of William Bent, who lived in Paternoster Row, London, were a most valuable source. These, together with the handwritten manuscripts of Thomas Hughes of Stroud (Gloucestershire), Thomas Stanwick of Derby, Sir George Shukborough-Evelyn of Shukborough, the Royal Society (then at Somerset House), Charles Soan of Clare Street, London, and the Modbury Diaries (author uncertain), are held at the National Meteorological Archives at Bracknell. These Archives also hold the collection of material forming Baker's *Record of the Seasons*. The log of HMS *Director* was prepared by Captain William Bligh, then recovered from the embarrassments of the '*Bounty* affair'. The vessel was then part of Admiral Duncan's North Sea fleet moored at Yarmouth Roads. This particular log was chosen because of Bligh's meticulous attention to detail, his seeming interest in the weather and, although a purely subjective assessment, the document's feel of accuracy. The log is held at the Public Records Office at Kew. The diary kept in Edinburgh by George Waterston is one of a number preserved in the Archives of the Royal Society of Edinburgh. The same Archives hold Robert Mossman's monumental accumulation of data and observations for Edinburgh including the volumes of the *Edinburgh Magazine* which contain some data used in this study. Numbers of the *Gentleman's Magazine* are held in the National Lending Library at Boston Spa. In addition to the written accounts, each month's edition also includes a statistical meteorological summary.

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The sensitivity of fine-mesh rainfall and cloud forecasts to the initial specification of humidity

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Summary

The problems associated with the objective analysis of humidity are discussed and a technique for amending the initial fine-mesh humidity fields is described which results in close comparison between the fine-mesh model cloud analysis and satellite imagery. Three case-studies illustrate the impact of the amended initial moisture fields on subsequent cloud and rainfall forecasts. The results of these and other cases allow us to conclude by suggesting circumstances in which the initial moisture specification is likely to be important.

1. Introduction

The humidity analysis is perhaps one of the weakest points of the operational data assimilation scheme for the fine-mesh model. There are several problem areas which have held back improvements in the objective analyses. The major difficulty is the deficiencies in the observing network which are particularly acute over the North Atlantic. At present the operational assimilation relies solely on humidity data from radiosondes, so the analysis over data-sparse areas is almost totally dependent on the background field provided by the model.

The objective use of other data types has been considered but their benefits have proved rather doubtful. The operational fine-mesh analysis has tried to make use of surface ship reports of dew-point in the past, but these are now excluded after it was found that reports indicating large positive humidity increments could occasionally trigger the convection scheme into giving large amounts of rain, with unfortunate consequences. In such cases the observations may have been perfectly valid but the model felt the influence of those increments over too large an area. One such case was the operational fine-mesh analysis for 1200 GMT on 26 December 1985 (Smith, personal communication). Other analysis schemes have attempted to make use of surface observations to infer humidity at upper levels. Illari (1986) describes how such reports are used in the analysis scheme from the European Centre for Medium-range Weather Forecasts (ECMWF) but at the same time notes that their use is highly empirical and of little value except perhaps in conditions of complete cloud cover. The ECMWF scheme also attempts to make use of the precipitable water content (PWC) information provided by the satellite soundings; however, the cases quoted by Illari to justify their use all involve tropical impact studies where the PWC is large. Clearly the precision demanded of the fine-mesh humidity analyses for accurate rainfall prediction cannot be achieved by relying on sounding data which give information over very thick layers (only two pieces of information to describe the moisture profile below 500 mb).

The dependence on model background in data-sparse areas gives humidity analyses whose characteristics follow closely the characteristics of the model. Bell (1986) discusses the deficiencies of the model profiles in the lower part of the atmosphere. Common problems noted include excessive moisture in moist south-westerly warm sector situations, excessive dryness in anticyclonic south-westerly flow, collapsed boundary layer in anticyclones, and excessive dryness above capping inversions. In our repeated-insertion data assimilation scheme, where the observation increments are used to nudge the model fields towards the observations during a forward integration of the model, the hope is that analysis fields remain consistent with what the model expects. Thus, even where observations are available, there will be a tendency for features which the model represents poorly to be also poorly represented in the analyses. Good analyses will only be obtained if the model background fields are realistic. Recent changes to the physical parametrization schemes (Hammon 1987) have gone some way towards improving the unrealistic features mentioned above.

One method of overcoming the problem of data sparsity is to generate bogus humidity reports based on information, such as satellite imagery and synoptic reports, which is not easily amenable to direct assimilation into the objective analysis. The interpretation in terms of relative humidity observations is very subjective. The intervention forecasters usually bogus in order to insert areas of high humidity indicative of cloud, but uncertainties in the value to be assigned as well as the depth of cloud make results unpredictable. The operational data assimilation scheme (Bell and Dickinson 1987) treates these bogus reports in a similar way to conventional radiosonde data. The observation increments are used at nearby model grid points in the horizontal to a range of about 600 km and in the vertical over several

model levels. In the statistical interpolation analysis, the weights given to the data as a function of distance from the observation position are determined according to a forecast error correlation which is quite broad. Thus, it is almost impossible to force the model to accept thin cloud layers or sharp discontinuities in the horizontal without saturation coverage of bogus humidity ascents. Some modest improvements in rainfall forecasts have been achieved using bogusing when applied with some care, particularly in the early stages of the forecasts (e.g. Smith 1986). But on other occasions the over-zealous intervention forecaster has done more harm than good. One such case was the fine-mesh forecast from 0000 GMT on 28 July 1987 which resulted in excessive rain over Scotland (Smith, personal communication).

The 10-level rectangle model analysis of relative humidity (Atkins 1974) included a non-isotropic weighting function dependent on the gradient in the background field in an attempt to retain sharper gradients in the humidity field associated with frontal rainbands. Unfortunately the statistical interpolation–repeated insertion scheme which replaced it has not proved very flexible and a similar approach was not carried over to the 15-level model. However, the revised repeated insertion algorithm (Lorenc *et al.* 1989) to be implemented during summer 1989 is more flexible.

In this paper, we are investigating the likely improvement in fine-mesh rainfall and cloud forecasts following a very detailed re-analysis of the model humidity fields. This re-analysis was univariate and no attempt was made to correct for any deficiencies in the mass and wind fields. Taking a lead from the mesoscale interactive analysis system (Golding 1988), we examined the analyses after the data assimilation stage and compared the model relative humidity fields and diagnosed cloud fields against cloud imagery and synoptic reports. We then simply amended each of the model levels directly as required in the area of study to make them compatible with what observations were available. The amendments were made directly to the model sigma-level fields so no further interpolation was required. Clearly a subjective interpretation of cloud base and top was still required and usually only one layer of cloud was catered for. Where cloud had to be removed, rather arbitrary values of 50–70% relative humidities were assigned. Where cloud was present, the model was assigned a value of relative humidity above the threshold used by the radiation scheme according to the same criteria used by that scheme, namely:

$$Q = (U - U_{crit})^2 / (1 - U_{crit})^2$$

where Q is the cloud fraction, U is the relative humidity when $U > U_{crit}$, and $U_{crit} = 85\%$ threshold relative humidity.

Eleven cases were chosen from those highlighted by forecasters during the past 2 years. For many of the cases, the forecasters in the Central Forecasting Office (CFO) provided a subjective cloud analysis giving base, top, geographical extent and degree of coverage. This is referred to here as the CFO cloud analysis. This cloud analysis was of great help in the preparation of the modified initial humidity field. We studied several cases for each type of situation likely to be encountered in the United Kingdom including frontal types, wave developments, convective cases and anticyclonic stratocumulus cases. All 11 cases are discussed in Bell and Hammon (1988). Here, we shall illustrate our findings by reference to three of those cases. Although we have concentrated for the most part on the evolution of cloud and rainfall, many other model products have also been examined.

2. A frontal case-study — data time 1200 GMT on 23 July 1987

During the 24 hours commencing 1800 GMT on 23 July 1987, a frontal system moved slowly southwards over the United Kingdom. Although accumulations were fairly small (no more than 5 mm), there were nevertheless persistent and locally moderate bands of rain associated with the warm and cold fronts. The radar picture (Fig. 1(a)) shows the rainfall distribution at 0600 GMT on 24 July, with the heaviest most widespread rain over northern England and southern Scotland. The narrow band of rain lying from East Anglia to south-west England is associated with the weaker warm front. As the cold front moved southwards, it weakened in the west, giving only a trace of rain over South Wales and south-west England, but the rain persisted in the east, especially over East Anglia.

This case was chosen because the fine-mesh model failed to predict the rainfall over the United Kingdom during the 24-hour period. In Fig. 1(b) we show the operational fine-mesh forecast of rainfall rates and surface pressure for T+18, which can be compared directly with the radar image. The forecast is much too dry over the United Kingdom, with the cold front rainfall non existent and the warm front rainfall confined to the North Sea.

The cause of this poor rainfall forecast is attributed partly to too much subsidence (the forecast pressure at T+18 is 2–4 mb too high over the United Kingdom), but mainly to dryness in the model's analysed relative humidity fields to the west of Scotland. In Fig. 2(a) we show the NOAA-10 visible satellite image for 0905 GMT on 23 July, showing the cloud areas to the west of Scotland. At this stage, the fronts seemed relatively weak, with little cloud showing on the infra-red image. The observed freezing levels at 1200 GMT were 12 000 feet over the United Kingdom ahead of the cold front, falling to 5000 feet well to the rear. The operational relative humidity analysis for 1200 GMT at 700 mb (Fig. 2(b)) shows that the frontal zone is defined in the model by only the 55% relative humidity contour and the model has only a small band of cloud associated with the front. The aim of intervention in this case was to improve the model's forecast rainfall associated with the cold front by increasing humidity in the analysis at

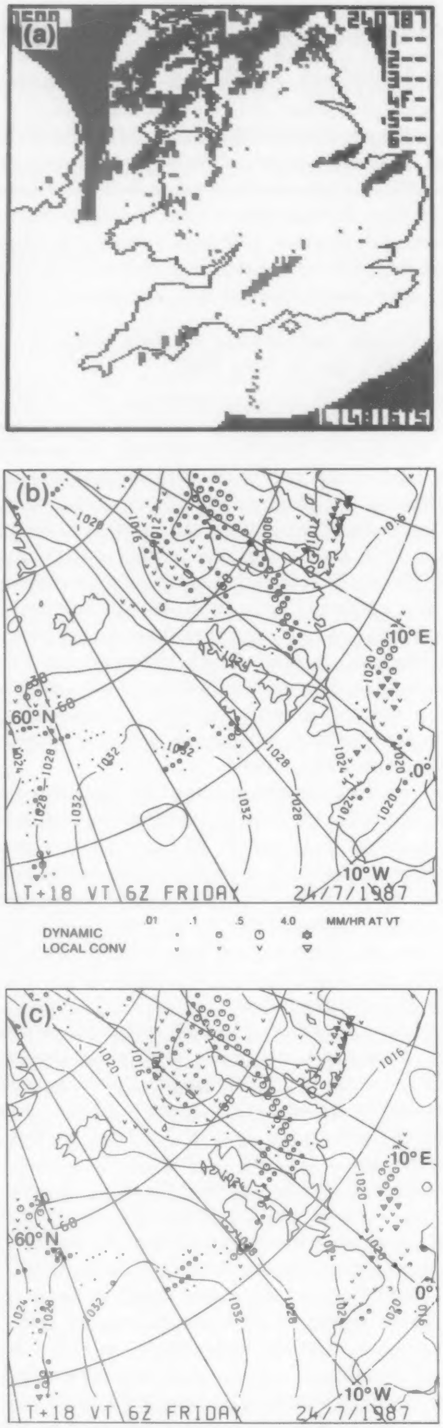
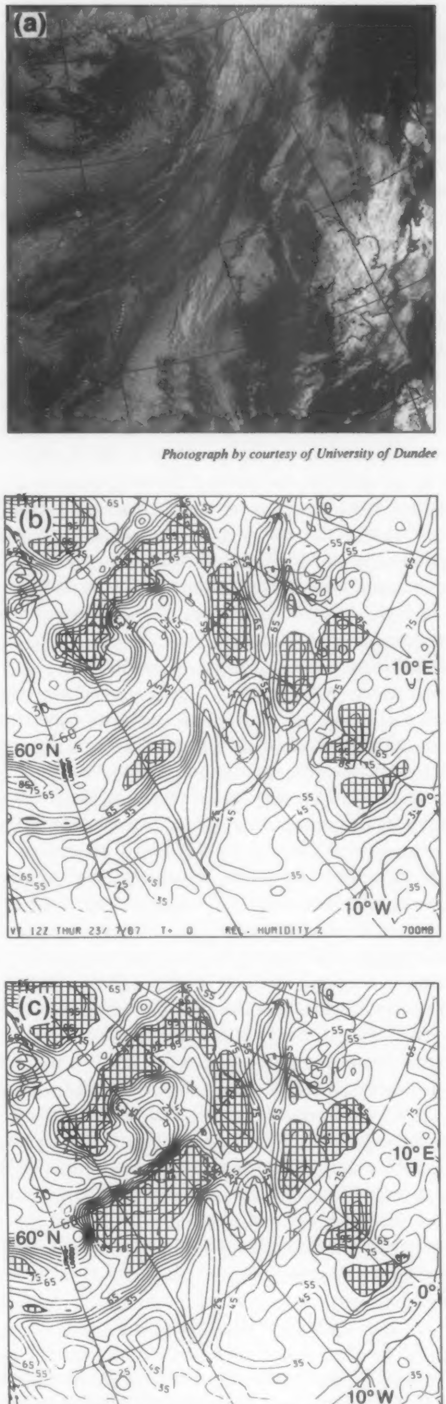


Figure 1. (a) Radar rainfall distribution for 0600 GMT on 24 July 1987, (b) operational fine-mesh forecast of rainfall rate (see key) and surface pressure (mb) for T+18 verifying at 0600 GMT on 24 July 1987, and (c) as (b) but based on modified analysis.



Photograph by courtesy of University of Dundee

Figure 2. (a) NOAA-10 visible satellite image for 0905 GMT on 23 July 1987, (b) operational fine-mesh analysis of relative humidity (per cent) at 700 mb for 1200 GMT on 23 July 1987, and (c) as (b) but after modification.

700 mb (level 6). We decided to increase the relative humidity at level 6 to 97% (approximately 5 oktas of cloud) in the analysis in the area bounded by 57–60° N, 05–25° W. The modified analysis is shown in Fig. 2(c).

The T+18 forecast based on the modified analysis (Fig. 1(c)) shows substantial improvements over northern England. The increased rainfall forecast over the United Kingdom on the cold front resulting from the modified analysis lasted at least to T+18. At T+24 the forecast rainfall west of the meridian had died out although slightly bigger amounts were forecast in the North Sea.

3. A wave development case-study — data time 1200 GMT on 19 August 1987

During the 18 hours from 1200 GMT on 19 August 1987, a cold front remained slow moving just to the west of southern Ireland, with its eastward progress retarded by a succession of waves moving up from the south-west so that eastern Ireland remained mostly dry until late in the night. The significant weather chart for 0000 GMT on 20 August (Fig. 3(a)) shows the observed rain area from one of these waves over Scotland and Northern Ireland at midnight, although a further wave brought rain back into south and west Ireland later.

The fine-mesh forecast from 1200 GMT on 19 August predicted the cold front and associated waves to be slightly too far east with heavy rain over eastern Ireland several hours too early. Fig. 3(b) shows the operational fine-mesh forecast of rainfall and surface pressure for 0000 GMT on the 20th. Comparing this with the corresponding significant weather chart, we see that the forecast rain area is too far advanced and in fact there is a timing error of at least 6 hours.

This timing error in the fine-mesh model forecast has been attributed mainly to a small spurious area of high humidity and cloud at 700 mb in the analysis at 47° N, 12° W, which we can see in Fig. 4(a). The modified analysis (Fig. 4(b)) had the relative humidity reduced to 80% in this area.

The T+12 forecast run from the modified analysis is shown in Fig. 3(c). The main impact has been to delay the forecast arrival of rain over central Ireland until after midnight. If we compare the forecasts at T+12, the modified forecast is more accurate over central Ireland but less over Northern Ireland. At T+18 (not shown), the operational and modified forecasts are very similar.

4. An anticyclonic stratocumulus case-study — data time 1200 GMT on 5 April 1988

On this occasion, an anticyclone was slow moving over the North Sea and northern England with a strong easterly air stream to the south. The Meteosat visible satellite image (Fig. 5(a)) for 1200 GMT on 5 April 1988 shows a large area of stratocumulus covering the North Sea and eastern England. Most of England and Wales, excluding the far west, had a cloudy night as stratocumulus continued to be advected inland from the

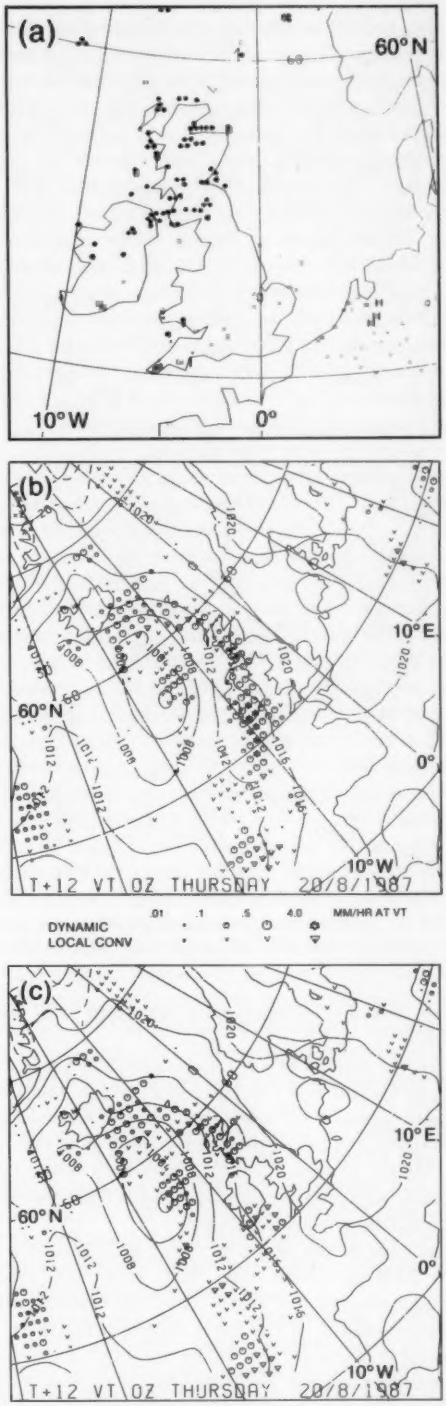


Figure 3. (a) Significant weather chart showing observed rainfall for 0000 GMT on 20 August 1987, (b) operational fine-mesh forecast of rainfall rate (see key) and surface pressure (mb) for T+12 verifying at 0000 GMT on 20 August 1987, and (c) as (b) but based on modified analysis.

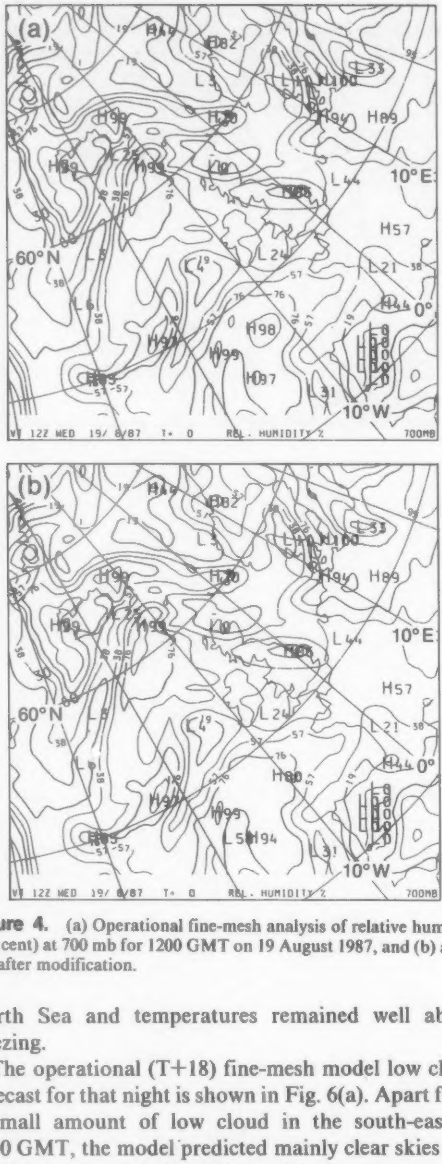


Figure 4. (a) Operational fine-mesh analysis of relative humidity (per cent) at 700 mb for 1200 GMT on 19 August 1987, and (b) as (a) but after modification.

North Sea and temperatures remained well above freezing.

The operational (T+18) fine-mesh model low cloud forecast for that night is shown in Fig. 6(a). Apart from a small amount of low cloud in the south-east at 0600 GMT, the model predicted mainly clear skies and the Model Output Statistics minimum temperature forecast incorrectly suggested a slight frost for south-east England and the Midlands.

The base of the observed cloud at 1200 GMT was 1500–2000 feet with tops 3000 feet. The model's inversion started at 950 mb. The 1200 GMT analysed relative humidity at 950 mb is shown in Fig. 5(b). The analysis is much too dry in the observed cloudy areas when compared with the visible satellite picture. A cloud layer was inserted by increasing the relative humidity at level 3 to 100% and this modified analysis is shown in Fig. 5(c).

The low cloud forecast run from the modified analysis is given in Fig. 6(b). Clearly there is a substantial

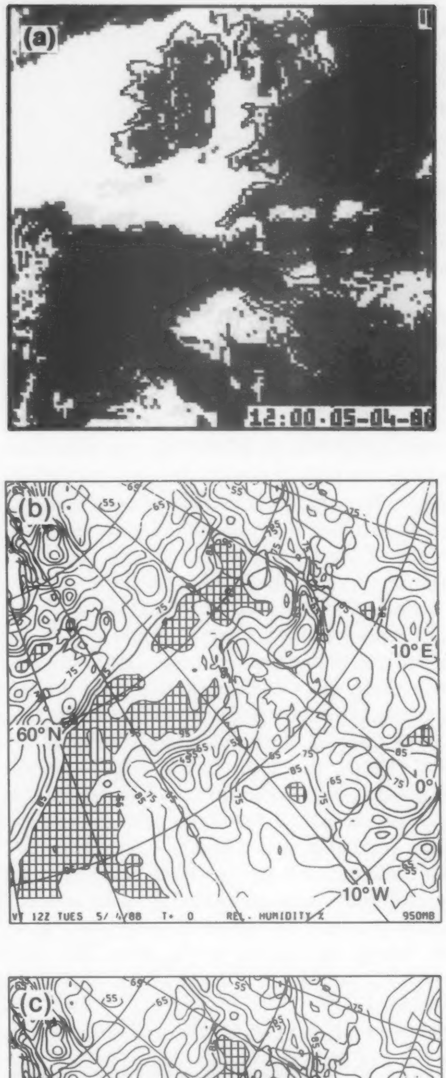


Figure 5. (a) Meteosat visible satellite image for 1200 GMT on 5 April 1988, (b) operational fine-mesh analysis of relative humidity (per cent) at 950 mb for 1200 GMT on 5 April 1988, and (c) as (b) but after modification.

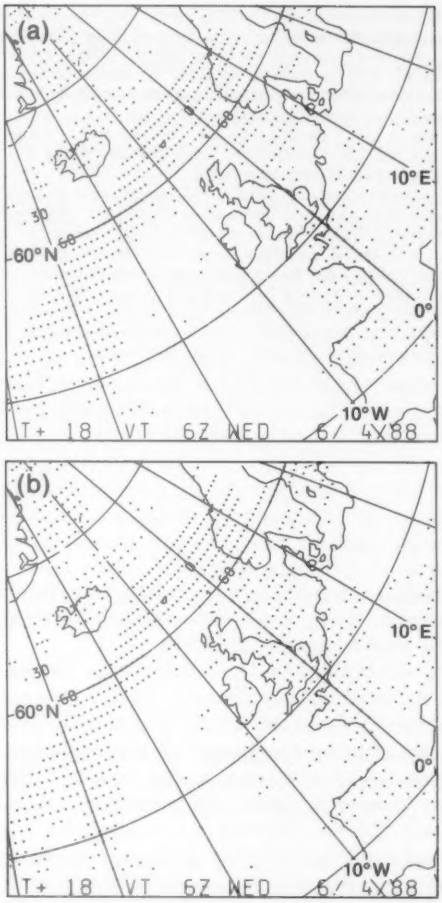


Figure 6. (a) Operational fine-mesh forecast of low cloud for T+18 verifying at 0600 GMT on 6 April 1988, and (b) as (a) but based on modified analysis.

improvement, with a complete cover of low cloud forecast over England and Wales and also more cloud over the North Sea. In this case, low cloud was added to the model analysis over the North Sea and overland in the United Kingdom to try to improve the forecast. The low cloud added overland disappeared within the first 6 hours of the forecast but the low cloud added over the sea remained. This cloud was advected across England and Wales during the forecast.

5. Concluding remarks

We have demonstrated that the relatively simple technique adopted here, involving the 'painting over' of the model relative humidity field after the assimilation stage, can result in a significant impact on the forecast rainfall on most occasions and also a noticeable impact on model cloud on some occasions when a problem with the initial moisture field has been noted. Where the addition of partial cloud cover was involved, we were careful to provide the model with a relative humidity value which could be interpreted as the same partial cloudiness in the model. We also avoided interpolation problems by inserting data at the model's sigma levels. In some instances we took careful note of the initial vertical profiles of moisture and temperature in order to insert information at a level where it would be most likely to be retained even if such a level was different from that inferred from the observations. This was particularly the case when thin layers of cloud were being inserted which needed to be correlated with changes in model lapse rate. The method adopted here gives much more control over the outcome than the conventional bogusing technique. The most difficult task is the interpretation of the satellite imagery in terms of model relative humidity fields. Ideally the imagery should be available reprojected on to the model grid before it can be fully useful. Clearly the technique could not be adopted for the main fine-mesh runs as there is not time to amend the fields; however, corrections to the assimilation cycle at an earlier stage are likely to remain useful in the following forecast run.

The frontal case demonstrated that the impact is greater in the first day and less towards the end of the forecast where presumably evolution errors begin to dominate. This result was supported by other case-studies, where noticeable improvements at T+18 were not evident at T+30. The wave development case presented here showed that erroneous waves can be suppressed. Other cases have shown that waves that are too weak can be emphasized. It was very clear in several frontal and wave cases that it was futile to try and adjust a fast-moving frontal system, or any case where the dynamical forcing was strong. Also no amount of tinkering with the initial moisture field could correct a serious positional error, which is likely to be related to an error in the initial mass and wind fields.

The impact in the anticyclonic case is less predictable. The main signal appears to be that some impact is obtained as long as the model's inversion is not too low (preferably at level 3) and the additional moisture is inserted over sea points. Inserting cloud over land or where the model inversion is very low does not appear to be very productive. It would appear that further improvements to the boundary-layer parametrization are required before observations of cloud can be retained in such cases. Some convection cases were also considered, but the impact on forecasts was very modest, indicating that deficiencies in the convective parametrization scheme are more likely to be the cause of poor forecasts of showers.

We did not attempt any compensating change to other model variables. Such changes might provide additional improvements if an appropriate method of achieving them could be devised. In the longer term, cloud liquid water is likely to be a prognostic model variable and the direct assimilation of cloud observations should be integrated with the assimilation of other observation types. The iterative nature of our assimilation

scheme will then allow the cloud observations to have an indirect impact on other model variables.

Acknowledgements

We are grateful for the help and encouragement provided by R.M. Morris.

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Reviews

Atmospheric tidal and planetary waves, by H. Volland. 163 mm × 246 mm, pp. x+348, *illus*. Dordrecht, Boston, London, Kluwer Academic Publishers, 1988. Price Dfl.210.00, US$99.00, £59.00.

The author aims to provide a unified view of wave-like planetary-scale oscillations of the earth's atmosphere between the ground and a height of about 400 km on time-scales ranging from 1 day to 11 years. Motivated strongly by the desire to obtain analytical solutions to the linearized primitive equations, he constructs idealized models of, for instance, the tidal and planetary Rossby wave response to prescribed heating functions, estimating typical magnitudes of the forcing and comparing the solutions with observations. Unlike most textbooks on dynamical meteorology, this one tackles the full rigours of Laplace's tidal equations by summarizing the findings of Longuet-Higgins (from his classic 1968 paper) and introducing a classification scheme for the various modes. The difficulty in this approach stems from the use of spherical geometry which, of course, is essential if one expects some quantitative agreement of wave periods with observations, but does not aid physical interpretation. The book does not set out to answer the question 'What is a gravity or Rossby wave?' — these distinct species of wave motion just emerge as different branches of a complicated dispersion relation.

The dominance of linear theory in the book, and planetary scales considered, leads to mathematical problems of the harmonic oscillator type for which resonance is possible; most of the nonlinearity is assumed parametrizable as Newtonian cooling or Rayleigh friction. By virtue of the geometry, series expansions in spherical harmonics are the principal representation of the horizontal structure of wave modes. It is nice to see all of the standard formulae required for manipulating associated Legendre functions in one place, though I would have preferred to see them for the usual normalized functions.

The author states in the preface that he has tried to treat the lower, middle and upper atmosphere on an equal footing. Given the vast range of densities covered (a factor of 10 for every 16 km of height) this can be disconcerting. For instance, in chapter 3 on 'External energy sources' one has to take in the size of the solar constant (and the one third of it available for driving tropospheric flows) in the same breath as a discussion on 'lunar gravitational tidal energy' which is tiny by comparison. The importance of electromagnetic forces in the ionized upper atmosphere reinforces the difficulty in giving equal emphasis to the different atmospheric layers. For those interested in learning a little about the motion of the ionized atmosphere (e.g. dynamo effect of tidal winds) I do not recommend reading the relevant sections of this book — too high a level of familiarity with the subject is assumed.

Chapter 7 on 'Nonlinear wave propagation' collects various ideas and theoretical treatments of nonlinear wave dynamics such as wave–wave interaction, two-dimensional turbulence, nonlinear normal mode initialization and the Lorenz attractor. There is even a subsection on a 'logistic difference equation' which has some bearing on the strange attractor. It looks interesting but seems out on a limb given the 'harmonic oscillator' feel to the rest of the book. It is a pity that more emphasis was not given to numerical simulation of large-amplitude planetary-scale motions when discussing nonlinearity — the topics discussed here are quite restricted.

On the positive side, one can only be impressed by the wide range of material covered, with sections on Ertel potential vorticity, Eliassen–Palm fluxes, length of the

day fluctuations and global angular momentum, El Niño and quasi-biennial oscillation — to mention a few familiar to the meteorologist. The author's combined understanding of the upper and lower atmosphere must be quite unusual. One must certainly respect his opinion on the long-standing and controversial subject of 'sun–weather relationships'. He states that most claims of correlations between solar indices and tropospheric disturbances are the result of the careless use of statistics.

Specific points of terminology that I found misleading were the use of the word 'interference' instead of 'interaction' and, that old favourite, 'standing' instead of 'stationary' (waves). The generally high standard of the physical explanations slipped in places with, for instance, on page 292 talk of 'the conversion of energy of waves with $m>0$ into fluctuations of the absolute angular momentum'.

I do not foresee a great demand for this sort of book but it does fill a gap in the literature and should be welcomed for that reason at least. Its highly technical content means that it will be used only by those active in research — particularly those with a passion for spherical harmonics.

G.J. Shutts

The geostationary applications satellite, by P. Berlin. 157 mm × 235 mm, pp. xvi+214, *illus.* Cambridge University Press, 1988. Price £30.00, US $49.50.

This book comprises 15 chapters describing the orbital dynamics, construction, payload, testing, launch and telemetry systems of satellites in geostationary orbits (at 36 000 km altitude). The author is an engineer rather than an applications scientist, and so for many meteorologists who come into contact with satellite data there is a considerable amount of jargon to master. However, this book represents a clear and successful attempt to introduce the non-specialist to satellite engineering, and a considerable amount of useful information is contained within the 214 pages.

Contained within the first chapter is an interesting account of how China acquired satellite expertise from the USA, enabling them to produce a launch vehicle, CZ-1, in spite of the McCarthy era of communist 'witch-hunting'. Further interesting facts emerge; for example, China's launch site is in Sichuan Province, and launch opportunities are confined mainly to the winter months due to the occurrence of heavy rainfall during the summer months. This is quite different from the European Ariane launch site at Kourou in French Guiana, where the hot and humid climate and the absence of hurricanes pose no limitation on launch opportunities. Likewise there are no weather problems at the USSR launch site at Baykonyr, 250 miles north-east of the Aral Sea in the Kazakhstan Republic, where very hot dry summers and cold winters are the norm. However, at Cape Canaveral in Florida thunderstorms may have to be monitored very closely around launch times.

Chapters 2 and 3 deal with orbital geometry and include a description of the geostationary orbit in which the sub-satellite point describes a figure-of-eight around the nominal longitude on the equator. There are interesting diagrams in chapter 4 showing accelerations during the ascent phase of launch. For example, for China's Long March-3 rocket, over 5 *g* is experienced within the first 200 seconds of flight compared with 4 *g* for the Ariane-4. The 'quality of life' of a satellite is described as being 'abysmal', the systems being subject to large accelerations, radiation, cosmic particle bombardment and electrostatic discharges.

Several short chapters follow, on the structure of satellites, the trade-off between usefulness and reliability in designing satellite mechanisms, thermal control (differences between active and passive), power supplies and propulsion. There is a longer description of attitude stabilization including gyroscopic theory — classical physicists will enjoy this! The problems of telemetry tracking, control and communications are outlined.

Chapter 13 deals with the meteorological payload. The description of a radiometer is of an infra-red detector. It is a pity that there is no mention of microwave systems. Whilst Meteosat is discussed, prospects for Meteosat Second Generation are, strangely, not mentioned. Unfortunately the section on meteorological data extraction is weak, although to be fair this is not the main thrust of the book. Statements such as 'air pressure can, to some extent, be inferred from wind speed and direction' are made, and the difficulties of extracting geophysical parameters from radiance measurements are glossed over.

The book concludes with discussion of product assurance which is useful to those not familiar with the 'bath-tub' curve of component failure rates. Likewise, for readers with only a passing contact with the procurement of complex instrumentation, the final chapter on spacecraft development and testing is a very useful introduction. A full schematic representation of an Ariane launch campaign is recorded.

Overall, this book is a useful reference to many of the things concerning geostationary satellites that meteorologists may come across. It is clearly written, but is somewhat unbalanced — chapter 6 is just over three pages long including figures, whereas chapter 10 is 28 pages. The reviewer did not notice any significant presentation errors and, whilst the meteorological section is disappointing, the book is to be recommended as a handy and practical guide to the subject.

C.G. Collier

Satellite photographs — 4 May 1989 at 0856 GMT

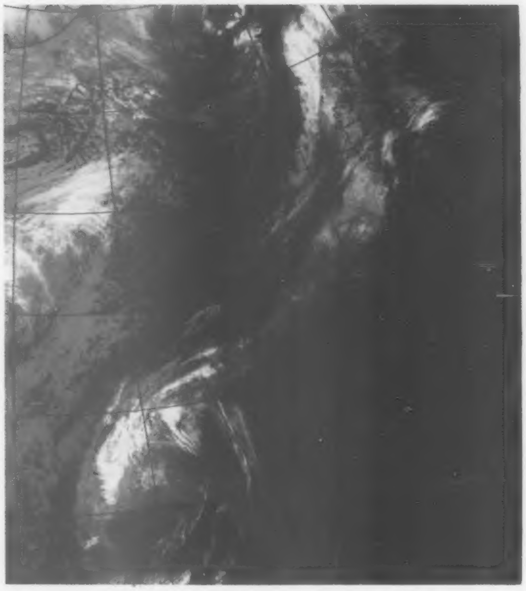

Figure 1. NOAA-10 infra-red image for 0856 GMT on 4 May 1989.

Figure 2. NOAA-10 visible image for 0856 GMT on 4 May 1989.

Photographs by courtesy of University of Dundee

A forecaster analysing the NOAA satellite imagery (Figs 1 and 2) in isolation from other data sources would be quite justified in concluding that low stratus and/or fog covered much of the southern North Sea and adjacent coasts (see Fig. 2). In reality, however, surface-based observations showed the area to be virtually cloudless, as it was on the satellite imagery 2 hours previously (not shown).

The conspicuous bright area on the visible image was in fact due to sun glint — the phenomenon caused by reflection from a calm or near-calm water surface. The synoptic situation for 0900 GMT (Fig. 3) shows that the area in question was under the influence of a slack easterly air stream, close to the centre of a high pressure cell. Sun glint can also be observed in Fig. 2 in the Bay of Biscay, particularly near the coasts of France and Spain. Another feature of interest on the visible image is the delineation of extensive areas of mainly low stratiform cloud associated with the weak fronts and warm sector of a system south-west of the United Kingdom.

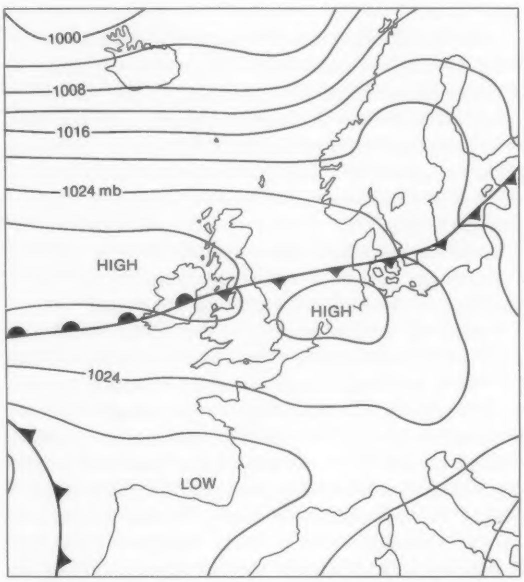

Figure 3. Surface analysis at 0900 GMT on 4 May 1989.

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Content

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References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

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Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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